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Solid state lighting review – Potential and challenges in Europe

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ABSTRACT

According to IEA estimates, about 19% of the electricity used in the world is for lighting loads with a slightly smaller fraction used in the European Union (14%). Lighting was the first service offered by electric utilities and still continues to be one of the largest electrical end-uses. Most current lighting technologies can be vastly improved, and therefore lighting loads present a huge potential for electricity savings.

Solid State Lighting (SSL) is amongst the most energy-efficient and environmentally friendly lighting technology. SSL has already reached a high efficiency level (over 276 lm/W) at ever-decreasing costs. Additionally the lifetime of LED lamps is several times longer than discharge lamps. This paper presents an overview of the state of the art SSL technology trends.

SSL technology is evolving fast, which can bring many advantages to the lighting marketplace. However, there are still some market barriers that are hindering the high cost-effective potential of energy-efficient lighting from being achieved. This paper presents several strategies and recommendations in order to overcome existing barriers and promote a faster penetration of SSL. The estimated savings potential through the application of SSL lighting systems in the European Union (EU) is around 209 TWh, which translates into 77 million tonnes of CO_2. The economic benefits translate into the equivalent annual electrical output of about 26 large power plants (1000 MW electric). Similar impacts, in terms of percentage savings, can be expected in other parts of the World.

Contents

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1. Introduction

1.1. Electricity consumption used for lighting in Europe and in the world

Global consumption of electricity has been increasing faster than the overall energy consumption because of the versatile nature of its production and consumption, as well as the relatively high efficiency and cleanliness at the point of use.

Lighting was the first service offered by electric utilities and still continues to be one of the largest electrical end-uses. Globally it accounts for 650 million tonnes (Mt) of primary energy consumption and results in the emissions of almost 1900 Mt of CO_2. This represents 70% of the emissions of the world's passenger vehicles and three times more than emissions from aviation [22].

Energy efficiency is one of the most effective means to solve these problems. It can both save energy and reduce greenhouse gas emissions (GHG). The European Union (EU) is committed to its new energy policy to improve energy efficiency by 20% by 2020 and is taking new measures for that purpose. These measures include minimum efficiency requirements for energy using equipment, as well as in buildings, industry, transport and energy generation.

The savings potential of lighting energy is very high with current technology, and it is even larger with new energy-efficient lighting technologies that are coming onto the market. Currently, more than 33 billion lamps operate worldwide, consuming more than 2650 TWh of energy annually, which is 19% of the global electricity consumption. Lighting uses a slightly smaller fraction in the European Union (14%) as can be seen in Fig. 1.

Globally, almost one-fifth of the total amount of electricity generated is consumed by the lighting sector. Almost half of the global lighting electricity is consumed by the commercial/tertiary sector, estimated at 1133 TWh representing 43% of lighting consumption. The rest is distributed amongst the residential sector with an estimated consumption of 811 TWh representing 31% of lighting consumption, the industrial sector with an estimated 490 TWh representing 18%, and the outdoor stationary sector with an estimated 218 TWh representing 8% of the total lighting electricity consumption [22] as can be verified in Fig. 2.

In the EU-27 countries lighting represents 14% of electricity consumption. The largest part of lighting electricity is consumed by the tertiary sector estimated at 164 TWh representing 40.2% of lighting consumption. The rest is distributed amongst the residential sector with an estimated consumption of 84 TWh representing 20.6% of lighting consumption, the industrial sector with an estimated 100 TWh representing 24.5%, and the outdoor stationary (mostly street lighting) sector with an estimated 60 TWh representing 14.7% of the total lighting electricity consumption as can be seen in Fig. 3.

1.2. Light sources

The largest amount of light, 64% of the total, is delivered by fluorescent lamps, which have efficacies in the range 40–100 lm/W. Fluorescent lamps are used mostly to provide general-purpose indoor lighting in tertiary and industrial buildings. However, in some countries (such as Japan) fluorescent lighting is also the main source of household lighting. Cultural traditions and preferences appear to play a large role in determining the choice of residential lighting systems, with significant implications for energy consumption. Fluorescent lamps account for 20% of global lamp sales and 45% of electric-lighting energy consumption. The next major group of lighting technologies is high-intensity discharge (HID) lamps, including mercury vapour lamps, high- and low-pressure sodium lamps and metal halide lamps. These high-power lamps provide large amounts of light at medium to high efficacy levels (35–150 lm/W) and are used primarily for outdoor lighting (including street lighting) and for indoor lighting in spaces with high ceilings such as in some industries. HID lamps account for 1% of global lamp sales, use 25% of global electric-lighting energy and provide 29% of the delivered light. Amongst HID lamps, mercury vapour lamps

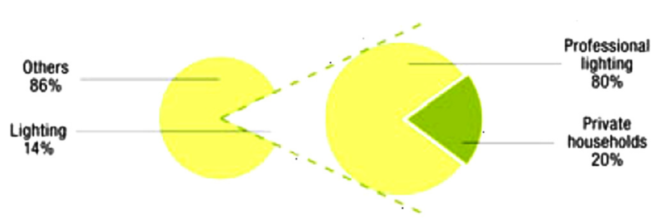

Fig. 1. Lighting electricity consumption in the EU.
Source: CELMA & ELC [5].

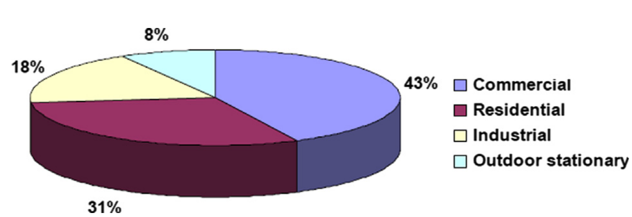

Fig. 2. World lighting consumption shares by sector in 2005.
Source: [22].

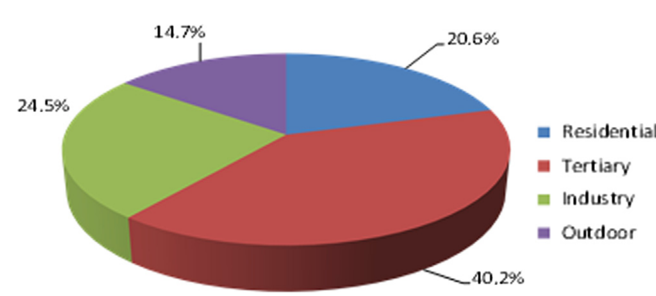

Fig. 3. Europe lighting consumption shares by sector in 2007.
Source: [55].

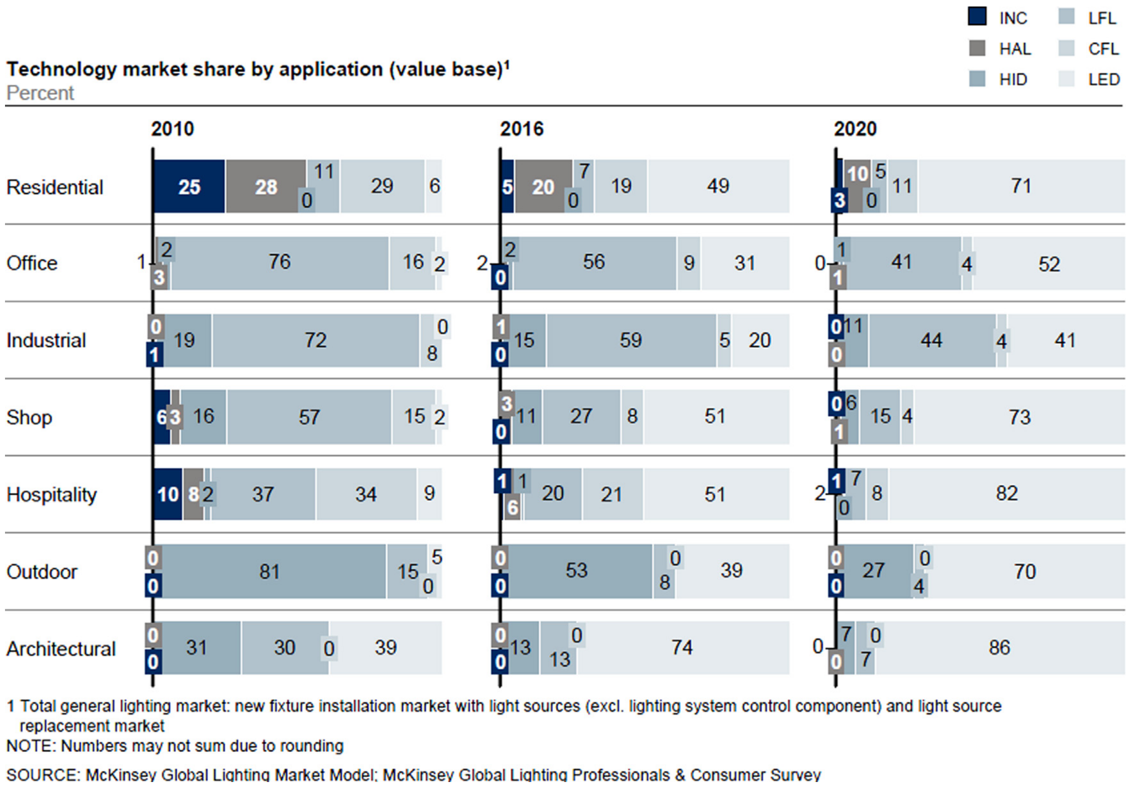

Fig. 4. Technology market share differs by application.
Source: McKinsey & Company, Inc. [26].

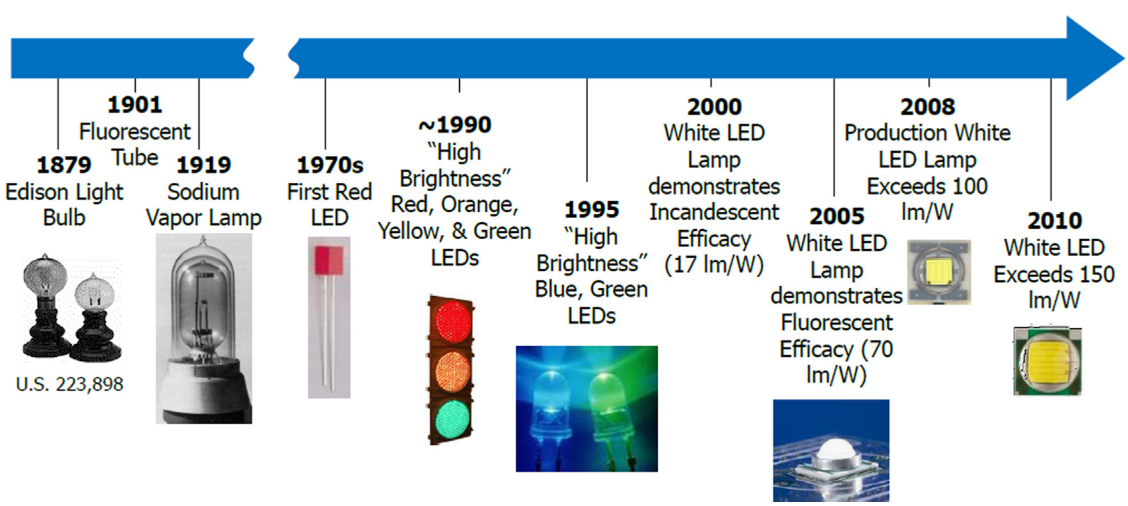

Fig. 5. Brief history of lighting, highlighting some milestones in LED development.
Source: [56].

constitute an old and inefficient technology which, despite having low cost-effectiveness compared with the alternatives, still accounts for a significant share of the total HID lighting applications. Both HID and fluorescent lamps are discharge lamps which require ballasts to regulate input voltages, frequencies and currents to enable the ignition and subsequent operation of the lamp. Ballasts need power in order to function, ranging from a few per cent to as much as 40% of the total lighting system consumption, depending on the efficiency of the ballast adopted. Because the efficacy of these various lighting sources varies so profoundly, their relative level of use has a large impact on the overall lighting energy consumption (Fig. 4) [27].

1.3. Technology evolution

Fig. 5 provides an overview of the history of lighting, showing three landmark technologies: I – Incandescent Lamps; II – Discharge Lamps; and III – Solid-State Lamps. Each of these technologies represented a drastic improvement over previous technologies. Despite the fact that LEDs were developed about 40 years ago, mostly for single colour applications, lighting applications became increasingly significant only in the last 10–15 years.

Since many current lighting technologies are highly inefficient, improved technologies for lighting hold great potential for energy savings and for reducing the associated GHG emissions.

Table 1
Lighting technologies' characteristics.
Source: [21].

Lamp type	Characteristics							
	Luminous efficacy (lm/W)	Lamp life (h)	Dimming control	Re-strike time	CRI	Cost of installation	Cost of operation	Applications
GLS	5–15	1000	Excellent	Prompt	Very good	Low	Very high	General lighting
Tungsten halogen	12–35	2000–4000	Excellent	Prompt	Very good	Low	High	General lighting
Mercury vapour	40–60	12,000	Not possible	2–5 min	Poor to good	Moderate	Moderate	Outdoor lighting
CFL	40–65	6000–12000	With special lamps	Prompt	Good	Low	Low	General lighting
Fluorescent lamp	50–100	10,000–16000	Good	Prompt	Good	Low	Low	General lighting
Induction lamp	60–80	60,000–100000	Not possible	Prompt	Good	High	Low	Places where access for maintenance is difficult
Metal halide	50–100	6000–12,000	Possible but not practical	5–10 min	Good	High	Low	Shopping malls, commercial buildings
High pressure sodium (standard)	80–100	12000–16000	Possible but not practical	2–5 min	Fair	High	Low	Outdoor, street lighting, warehouse
High pressure sodium (colour improved)	40–60	6000–10000	Possible but not practical	2–6 min	Good	High	Low	Outdoor, commercial interior lighting
LEDs	20–120	20,000–100000	Excellent	Prompt	Good	High	Low	All in near future

The lighting picture of today is still dominated by standard lighting devices. They are widely spread, well known, and have a well-established distribution infrastructure, their application often being based on lm/€ values. The transition phase to advanced lighting technologies has already started. These are driven by huge improvements of lamps' performance with respect to efficacy, lifetime robustness and cost (Table 1) [20].

Conventional incandescent bulbs, which convert about 4–5% of the electricity they consume into usable light (when compared with the maximum efficacy of 408 lm/W for a near white light source), have been the initial focus of policy attention. This attention is clearly justified, since households and the tertiary/commercial sector are responsible for over half of the EU's total electricity consumption.

With the phasing out of incandescent lamps in the EU as well as in many other countries simultaneously, the introduction of Solid-State Lighting (SSL) namely new LED-based light sources (lamps, modules) and luminaires shows great promise as a source of efficient, affordable, and colour-balanced white light [3].

SSL is a "breakthrough" lighting technology that can help drastically reduce the consumption of energy for lighting compared to the existing, conventional lighting technologies, whilst improving light quality, as well as reducing maintenance costs. Energy savings can be further increased with intelligent light control to minimize wastage, increase convenience and safety.

1.4. LEDs for solid-state lighting

SSL based on LEDs is an emerging technology with potential to greatly exceed the efficiency of traditional lamp-based lighting systems. Whereas energy efficiency is the primary motivation behind SSL, LEDs are also anticipated to bring entirely new functionalities to lighting systems, greatly enhancing the ways in which we use light. LEDs have already replaced traditional lamps in a number of lighting systems, including traffic lights, signs, and displays [9].

The light emitting diode (LED) is versatile in many different applications and can already be found in a range of applications where reliability, colour, visibility and long life are important. LEDs can now be found in signal lighting, traffic lights, automotive lighting, computer monitors, mobile phones and in home entertainment. More recently, LED applications have been encompassing street and decorative lighting, indoors and outdoors.

LED technology is known for a host of performance advantages, including outstanding energy efficiency, optical efficiency, less weight and packaging due to a compact design, and increased reliability and flexibility. This flexibility allowed LEDs to be used in applications where standard lamps would not work. Now, convinced of the potential in other areas, lamp manufacturers are undertaking a significant amount of development work on LEDs for a whole range of applications. LEDs emit light by the movement of electrons in a semiconductor material, which converts electric current directly into light. In contrast to incandescent lamps, that produce a continuous spectrum of light, the LED semiconductor emits light of a particular colour or wavelength depending on the material used at the base of the chip. Like many other recent solid state technologies, LEDs are continuously developing and improving in performance (Fig. 6), already overtaking the efficiency of other light sources and functioning in ways that could not be done before and with clear benefits to society as a whole [38].

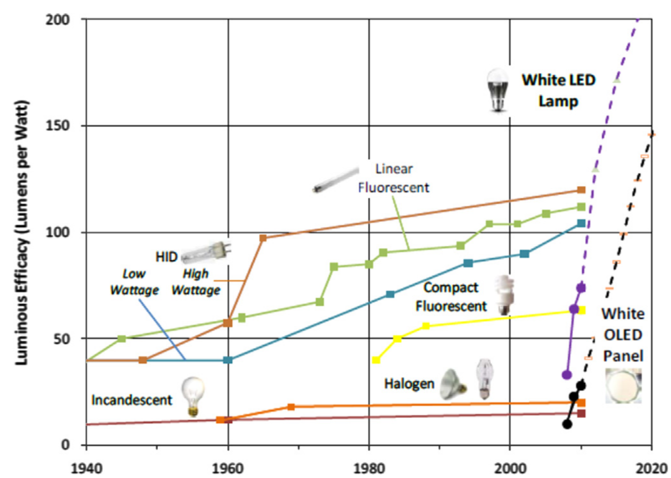

Fig. 6. Historical and predicted efficacy of light sources.
Source: [35].

1.5. Advantages and disadvantages of LEDs

The advantages of LEDs, compared with other light sources, are as follows:

- High efficiency, low power consumption and low operating voltage;
- Good physical robustness and compactness;

- Small weight and size (but heat sink can be large for high power models);
- Long lifetime expectancy (25,000 to over 50,000 h of life). With special design, lifetimes of 150,000 h can be achieved;
- Instantaneous switch-on with no re-strike time;
- Mercury-free;
- High luminous efficacy;
- New luminaire design possibilities;
- Vivid colour range and control;
- Easily dimmable;
- No UV or IV radiation;
- Rapid on/off time and no disadvantage when used for cycling applications.

The main disadvantages of LEDs are as follows:

- Lack of standardization;
- Relatively high price;
- Risk of glare as a result of small lamp size;
- Need for thermal management to avoid degradation in lifetime;
- Blue pollution (this applies for cool-white LEDs which can cause light pollution);
- Temperature dependence (ambient temperature greatly influences the LEDs' performance) [21,16,49].

1.6. Applications for solid-state lighting

Initially the market was dominated by signalling and display applications. Mobile, automotive and entertainment applications followed, with lighting applications becoming more and more diversified in the last decade. New possibilities in Decorative and Architectural Lighting were presented by SSL, due to their superior colour and special distribution capabilities, as well as lower maintenance costs and improved design possibilities.

The use of LEDs is also becoming more common in Tertiary Buildings, to replace tubular fluorescent, CFL and halogen incandescent lamps. Energy savings vary over a wide range. In the replacement of halogen incandescent lamps, high efficiency LEDs cut the energy consumption by a factor of up to 10.

Besides higher efficiency, LEDs in buildings can offer the following:

- Less radiated heat (very relevant for display lighting of most items);
- Lower waste heat leading to reduced air conditioning requirements;
- Lower maintenance costs;
- Improved design possibilities.

Street lighting is one of the fast growing application sectors for LED technology. The potential advantages include the following:

- Reduced energy costs (about 50% compared with HPSV – High Pressure Sodium Vapour lamps);
- Lower maintenance costs (lifetime of well-designed LED luminaires can be 3–6 times longer than that of HPSV lamps);
- Improved colour rendition, leading to increased visual acuity and safety;
- Less light spillage (leading to higher system efficiency) and less light pollution due to the more directional light output of LEDs.

The estimation of the energy saving potential of LED technology for street lighting strongly depends on the existing system technology in a community or in a city. Street lights in Europe can be equipped with high pressure sodium lamps, mercury vapour lamps, or compact fluorescent lamps.

2. SSL penetration in Europe and the world

2.1. LED application trends

Fig. 7 shows the general trend in the application of LEDs (mostly High Brightness) spreading in three large areas:

- Phase I: Mobile appliances, such as laptops and mobile phones in which the higher component cost is justified by the longer battery autonomy, as well as better display quality.
- Phase II: Large displays, such as TVs and computer monitors, which by 2010 have transformed the market from CRT to flat screen technologies (Plasma, LCD with fluorescent backlighting and LCD with LED backlighting).
- Phase III: General illumination covering a wide variety of applications, as shown in Fig. 8, which also shows a time scale of product availability as well as the timing of broad product acceptance.

2.2. LED lighting market trends

LEDs will be used to build a variety of lamps, which can be applied in a wide array of applications. The world market for lamps (all technologies) will be at a level of € 17 billion in 2015 [5] (Fig. 9).

The overall lighting market declined by about 15% in 2009 due to the economic recession, but the LED lighting lamp and luminaire market grew robustly at 32%. In 2010 the global market for lighting products was estimated to be approximately € 80 billion, of which a very small, but fast growing, fraction is related to LED systems [50].

Hundreds of companies worldwide are participating in the LED luminaire and replacement lamp market. Major outdoor area and commercial retrofit adoptions are taking place. The larger lighting companies have introduced LED products and design approaches for LED fixtures and light engines are becoming more sophisticated. LED-based fixtures are already available with key quality indicators that nearly meet or exceed every other indoor lighting technology, except on initial cost.

Products in the market are still highly variable in terms of quality, but are improving. The industry is still plagued by many low-quality and/or underperforming LED fixtures. Standards setting is moving rapidly, but needs consistency between regions. The product interfaces have not been standardized – drivers, dimmers, and controls are difficult to navigate.

It is also expected that the LED luminaire design will evolve. As Fig. 10 shows, integrated luminaires (for indoors and outdoors) dominate the market today but during the next 5–10 years light

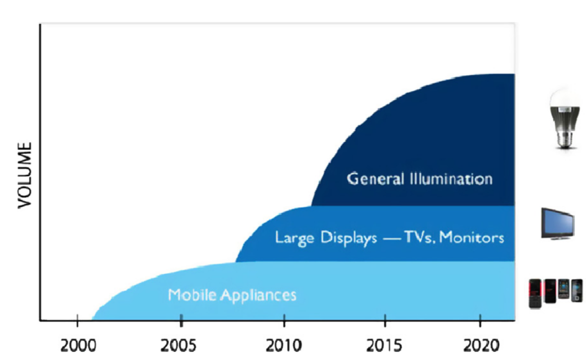

Fig. 7. LED application trends.
Source: CELMA & ELC [5].

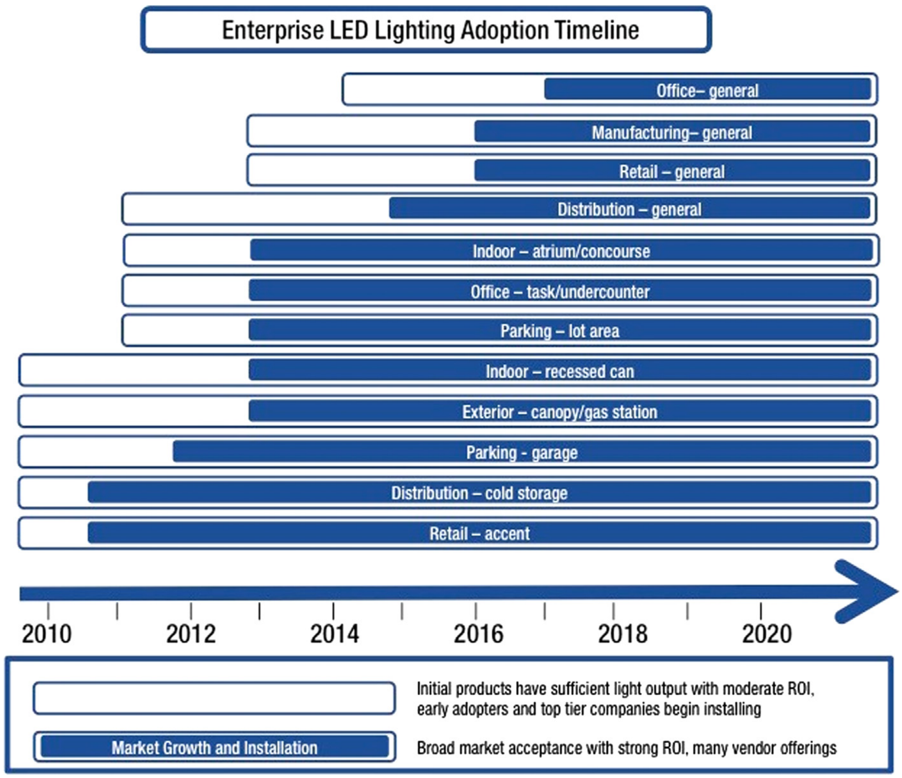

Fig. 8. Enterprise LED lighting adoption timeline.
Source: [19].

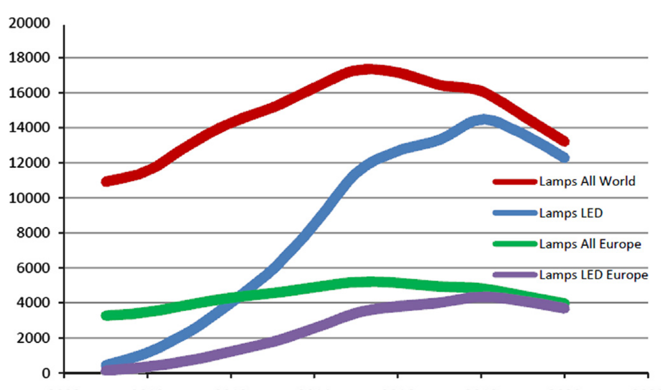

Fig. 9. Lamps market, world & Europe [Million EUR].
Source: CELMA and ELC [5].

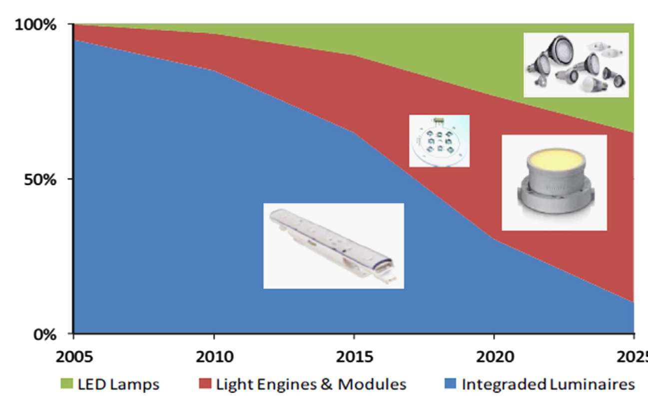

Fig. 10. LED luminaire design evolution.
Source: [8].

engines, modules and finally LED lamps will take a major part of the market.

2.3. SSL technology evolution and costs

LED technology is evolving very fast in terms of performance and costs. Fig. 11 and Table 2 show the relative and absolute comparison of lighting technologies' technical characteristics.

Today the efficacy of a commercial cool white LED is already well over 100 lm/W. These advancements will come from improvements in internal quantum efficiency (the ratio of injected electrons to emitted photons in the active region), extraction efficiency (the efficiency of extracting generated photons from the active regions out of the packaged part), phosphor advancements, and improvements in scattering efficiency (the efficiency of extracting photons from the phosphor versus all the photons coming from the chip). In addition to improvements in efficiency, improvements in packaging are increasing the lifetime of LEDs to 30,000–50 000 h [3].

Fig. 12 shows the US DoE LED package efficacy targets at the laboratory and commercial level. It is foreseen that by 2020, both commercial cool and warm white LEDs will approach 250 lm/W, which is more than double the efficacy of the best fluorescent lamps.

The above projects are subject to a level of uncertainty. There are reasons to believe the higher projections, since in February 2013, Cree announced a prototype with 276 lm/W efficiency at 350 mA.

Fig. 13 shows a similar projection, but relatively less ambitious, of the Optoelectronics Industry Development Association (OIDA) Solid State Lighting Efficacy Roadmap, including lamp/luminaires for warm white LEDs.

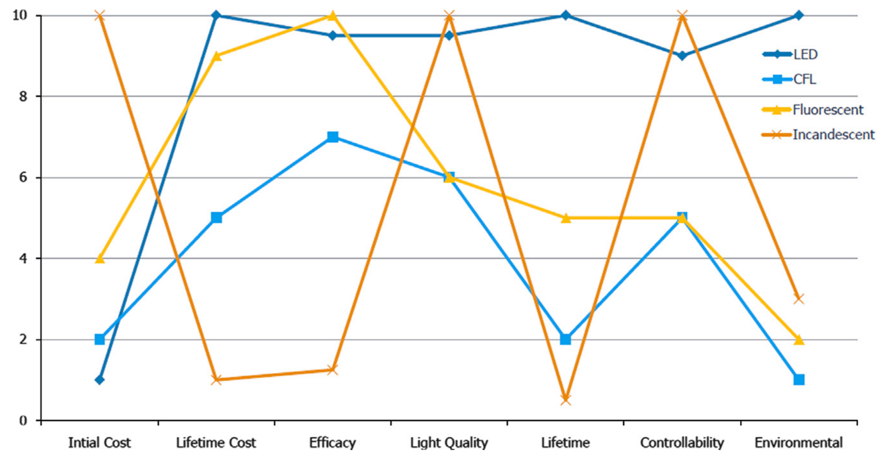

Fig. 11. Comparative SSL technology status vs. other technologies.
Source: [57].

Table 2
Lighting technologies' technical characteristics.
Source: [42].

Product type	Luminous efficacy	Luminous output	Wattage	CCT	CRI	Lifetime
LED white package (cool)	130 lm/W	130 lm	1 W	5650 K	70	50 kh
LED white package (warm)	93 lm/W	205 lm	2.2 W	3500 K	80	50 kh
LED A19 lamp (warm white)	64 lm/W	800 lm	12.5 W	2700 K	80	25 kh
LED PAR38 lamp (warm white)	52.5 lm/W	1050 lm	20 W	3000 K	80	25 kh
OLED panel	28 lm/W	50 lm	2 W	2700–6500 K	80	8 kh
HID (high watt) Lamp and Ballast	120 lm/W 111 lm/W	37,800 lm	315 W 341 W	3000 K	90	20 kh
Linear fluorescent lamp and ballast	118 lm/W 108 lm/W	3050 lm 6100 lm	26 W 56 W	4100 K	85	25 kh
HID (low watt) Lamp and Ballast	104 lm/W 97 lm/W	7300 lm	70 W 75 W	3000 K	90	12 kh
CFL	63 lm/W	950 lm	15 W	2700 K	82	12 kh
Halogen	20 lm/W	970 lm	48 W	2750 K	N/A	4 kh
Incandescent	15 lm/W	900 lm	60 W	3300 K	100	1 kh

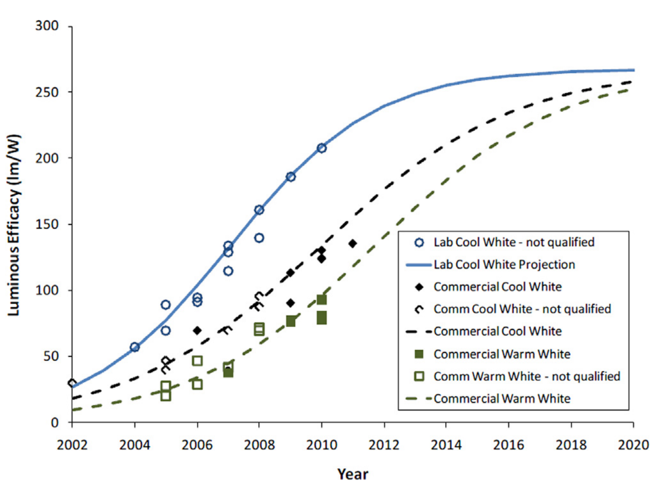

Fig. 12. LED package efficacy targets, laboratory and commercial.
Source: [42].

Fig. 14 shows the relative packaged LED cost track projections considering the different shares of the components. According to Lux Research[1] with innovation in areas such as thermal management, drivers, and optics the cost of LED bulbs will fall to about 8 Euro (US$11) by 2020.

[1] http://www.luxresearchinc.com/

Fig. 15 shows the absolute (€/lm) LED package projected market costs in Europe.

Dr. Roland Haitz presented in the 2000 Conference Strategies in Light the prediction of exponential development of cost per lumen and amount of light per package; the publication also predicted that the efficiency of LED-based lighting could reach 200 lm/W in 2020 crossing 100 lm/W in 2010. This would be the case if enough industrial and government resources were spent for research on LED-lighting. More than 50% of the electricity consumption for lighting (about 20% of the totally consumed electrical energy in the world) would be saved by reaching 200 lm/W. This prospect and other stepping-stone applications of LEDs (e.g. mobile phone flash and LCD-backlighting) led to a massive investment in LED-research such that the LED efficiency did indeed cross 100 lm/W in 2010.

Haitz's Law is an observation/prediction about the steady improvement over the years of LEDs. It states that every decade, the cost per lumen (unit of useful light emitted) falls by a factor of 10 and the amount of light generated per LED package increases by a factor of 20 for a given wavelength (colour) of light. It is considered the LED counterpart to Moore's Law, which states that the number of transistors in a given integrated circuit doubles every 18–24 months.

Fig. 16 shows in a logarithmic scale the remarkable evolution in reality, over more than four decades, of the projections of Haitz's Law, demonstrating the exponential trends – LED light output increasing/cost decreasing. In reality the light output per package has exceeded the projections.

Table 3 shows the LED package price per klm and performance projections for this decade made by the US DoE.

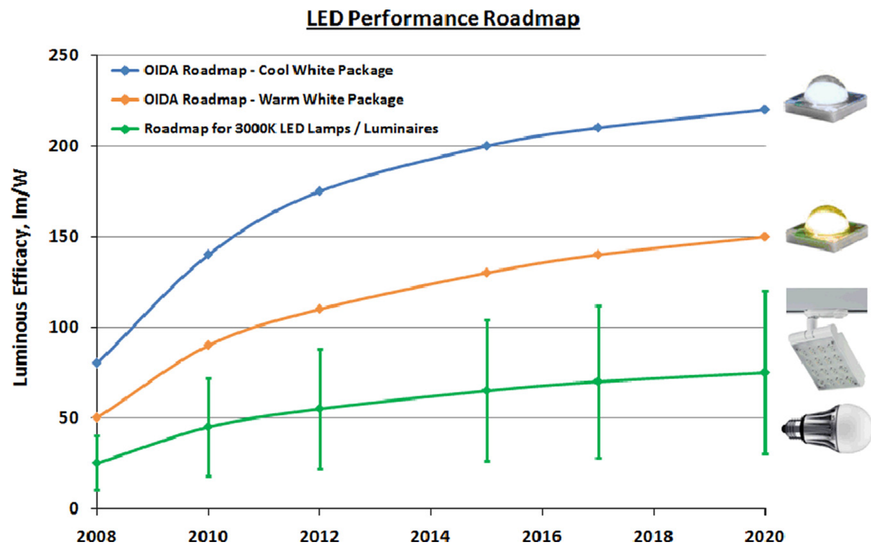

Fig. 13. Solid state lighting, including lamp/luminaires: efficacy roadmap.
Source: CELMA & ELC [5].

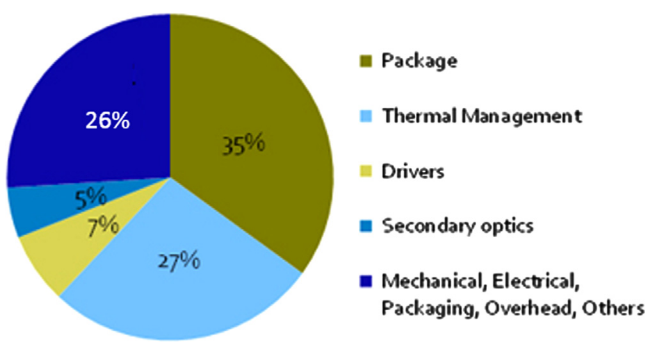

Fig. 14. LED bulb cost breakdown.
Source: [29].

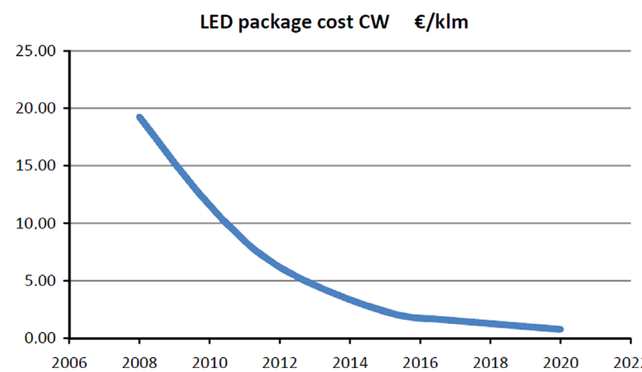

Fig. 15. LED: projected market cost.
Source: CELMA & ELC [5].

During this decade, a reduction in the LED package cost in the order of 10 times can be achieved. The path to achieve cost reductions of a LED package is shown in Fig. 17.

3. Barriers to SSL development and policy options for European leadership

3.1. Barriers for the implementation of SSL

The following lists some of the technical, cost, and market barriers to LEDs. Overcoming these barriers is essential to the rapid market deployment of SSL.

- Cost: The initial cost of LED-based general illumination sources is still too high, in comparison with conventional lighting technologies. Prices are kept high due to the smaller scale of production and also due to a high demand for LED in other applications like automotive and displays. Since the lighting market has historically been strongly affected by first cost, although their life cycle cost may be lower due to their long lifetime and high-energy efficiency, lower cost LED packages and luminaire materials are needed, as well as low-cost, high-volume, and reliable manufacturing methods. One trend is the continuing decline of LED retail prices, dropping at a rate of 20–25% per year compared to incumbent technologies, in which prices are flat or are declining much more slowly. A narrowing price differential between LEDs and more traditional forms of lighting is therefore slowly removing one of the key barriers to mass adoption.
- Payback time: The payback time is the time necessary for a LED customer to break even on his/her investment in a more expensive LED bulb. Based on extensive research in Japan where energy prices are very high, thus lowering the time to payback for more efficient bulbs, customers have a 10% chance of adopting a technology if payback is 2 years, a 30% chance if payback is 1 year, and a 40% if payback is 6 months. Therefore, the time to payback metric helps to predict LED adoption with some historical and empirical accuracy. The fact that payback periods are shrinking along with LED retail prices will ensure significant market penetration (50%+) in the next decade.
- Quality: The market is flooded with LED luminaires and replacement lamps of questionable quality (low efficacy, poor colour rendition, and short lifetime). Establishing consumer confidence is a key factor for the development of the LED lighting market. Well-known problems incurred with "non-mature" CFLs are poisoning of the market and the customer not feeling confident of new technologies.[2]
- Luminous efficacy: The luminous efficacy (lm/W) of LEDs is already above 200 lm/W, but it can still improve. Although the

[2] The EU LED Quality Charter is an attempt to address this issue.

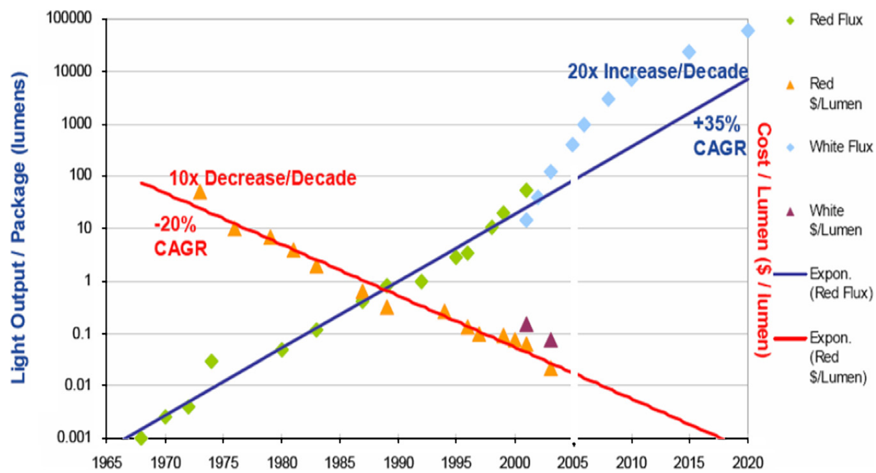

Fig. 16. Haitz's law: Exponential trends – LED light output increasing/cost decreasing.
Source: [2].

Table 3
LED package price and performance projections.
Source: [44].

Metric	Unit	2011	2012	2013	2015	2020
LED package efficacy (warm white)	lm/W	97	113	129	162	224
LED package price (warm white)	$/klm	12.5	7.9	5.1	2.3	0.7
LED package efficacy (cool white)	lm/W	135	150	164	190	235
LED package price (cool white)	$/klm	9	6	4	2	0.7
OEM lamp price	$/klm	33	23	16.5	10	5

Notes:
1. Projections for cool white packages assume CCT = 4746–7040 K and CRI = 70–80, whilst projections for warm white packages assume CCT = 2580–3710 K and CRI = 80–90.
2. All efficacy projections assume measurements at 25 °C with a drive current density of 35 A/cm^2.
3. Note that MYPP projections are based on price, not cost.

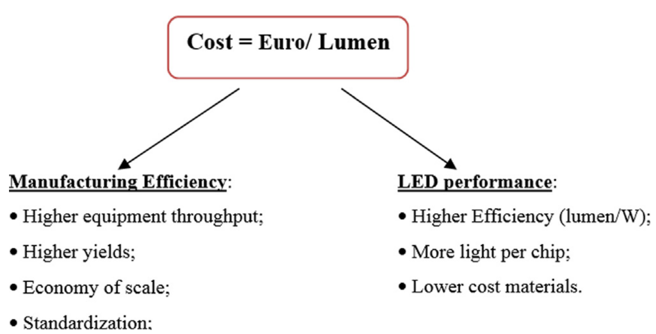

Fig. 17. Path to cost reduction.
Source: Adapted from [47].

luminous efficacy of LED luminaires has surpassed that of the incandescent and compact fluorescent lamps, improvement is still needed to compete with other conventional lighting solutions and to maximize the energy savings from this technology. The efficacy of commercial LEDs is not yet near its fundamental limit. Further improvements in LED efficacy can lead to even greater energy savings and can impact the cost of SSL sources, which can accelerate adoption of efficient LED products. In general, improving the efficacy of the LED impacts the number of LEDs required for the lighting application, as well as the thermal handling demands in the LED luminaire, thus reducing costs.

- Lifetime: A definition of lifetime that focuses on lumen maintenance is inadequate for luminaires. Lumen maintenance is only one component of the lifetime of a luminaire that may be subject to other failure mechanisms, such as colour shifts, optics degradation, or even catastrophic failure. How the LED is incorporated into the luminaire design can also have considerable impact on the lifetime of the system, inadequate thermal handling can reduce the LED lifetime and the design of the power supply can also impact the lifetime of the LED. A better understanding of the luminaire system lifetime and reliability is necessary for accelerated adoption of energy saving LED-based light sources.
- Educational barriers: LED-based lighting remains a new technology that is not well known in the marketplace. This unfamiliarity applies equally for users at all experience levels: lighting designers, residential and commercial users, installers, building inspectors, and government code officials. Most lighting designers are used to thinking, designing, and working with white light sources, instead of coloured light sources. They are also not accustomed to taking advantage of the energy-efficiency, long-life and maintenance characteristics of LEDs.
- Testing: The reported lumen output and efficacies of LED products in the market do not always match laboratory tests of performance. Whilst standardised testing protocols for performance metrics have been developed for light output, colour and efficacy, there are still many products that do not match the stated performance claims. The US Department of Energy (DOE) has supported the development of the Lighting Facts Label to standardize performance reporting. Still, an important barrier for luminaire integrators appears to be the difference in stated LED device specifications versus the actual LED performance at continuous operation in a luminaire. LED manufacturers have begun to address this problem by providing "hot" performance data on the LEDs. Furthermore, accelerated reliability testing methods for systems and materials

would greatly reduce costs and time-to-market. Such tests, capable of providing accurate projections of life, do not currently exist. Uncertainty, in both device and luminaire lifetimes, creates risk for manufacturers and consumers, potentially reducing adoption rates.

- Manufacturing: Lack of process and component uniformity will be an important issue for LEDs and is a barrier to reduced costs, as well as a problem for uniform quality of light. LEDs still have a number of technological hurdles to overcome. Additional work also remains to be done in the systems' design and integration area before LEDs can fully compete as a viable light source in the general lighting market. A few years ago no consistent approach to creating a LED system existed, but now this issue is under solution.
- Lack/high cost of capital: This traditional market barrier is associated with the lack and/or high cost of capital required to make larger investments in the implementation of LED lighting systems.
- Aversion to risk: The uncertainty of product performance, particularly the required lifetime to justify the investment, can negatively influence decision-makers.
- Lack of time: Most users of lighting systems are time-constrained and have to weigh up the benefits of optimizing their information and decision-making about lighting systems against many other competing demands on their time. This is particularly true for SMEs.
- There is one final threat linked to the impact of the phase-out regulations of which policy-makers should be aware. The total number of lighting products sold will fall dramatically. This fall will be greatest in those markets that currently have low penetrations of LEDs (or CFLs) and where these products are adopted rapidly. However, a fall in sales should be noticeable in all markets where regulations cause the substitution of (generally) short lifetime, inefficient lamps with more efficient, longer life alternatives. Such a fall in sales is already being witnessed in Australia and the UK. Without a full model of the installed stock in each country, it is impossible to predict accurately what the ultimate levels of sales will be. But for the UK it is estimated that the total number of lamp sales in 2014 will be 75% lower than the total lamp sales in 2009 if current trends continue.

Sources: CELMA & ELC [5]; Ecos Consulting [15, 22, 42], de Almeida et al. [12].

3.2. Strategies for the further development of SSL

Although a number of EU Member States have taken measures, especially in the field of funded scientific research, the future challenges related to market penetration, international benchmarking, as well as definition and implementation of technological leadership have to be addressed on a European level [5]. The need for concerted and integrated European policies is also obvious when looking at the supply and demand side of industry, and can be addressed by the following strategies:

- **Collaborative effort is needed to increase the performance of SSL solutions**: from LED chip, lamp to luminaire and lighting solutions – cost and quality are in focus. The lighting and small and medium enterprises based luminaire industry needs to act at the European scale to overcome fragmentation and to gain critical mass in the latest SSL development and broad deployment;
- **Support of a value chain approach**: A lot of emphasis has been placed on breakthrough research (e.g. FP6 and FP7 Programmes) and less attention on the cost intensive downstream activities of industrialization and commercialization, i.e., applied research, system integration and market validation;
- To assure a broader acceptance of SSL, there is a need to establish **European Standards, Labels and Quality Schemes** jointly with the EU industry.
    - **Improved harmonized test standards** addressing all key aspects of SSL lighting performance (namely efficacy, lumens, watts, correlated colour temperature (CCT), colour rendering index (CRI) and lifetime) are required to ensure a level playing field for a competitive market;
    - **Minimum efficiency performance standards** to remove from the market products; existing lighting standards should be expanded at the EU level (harmonized if possible through international cooperation) to cover other products and sectors with progressive stringency levels, as SSL technology develops;
    - **Energy labels** such as those of the European Union LED Quality Charter or ENERGY STAR are very important in establishing minimum performance levels, ensuring the credibility of SSL products;
- **Market surveillance**: As compliance with European requirements is based on self-certification by the manufacturer or distributors, market surveillance by the EU Member States seems crucial to avoid unfair competition and customer dissatisfaction.

In particular in the case of LED lighting products (where a new product generation might be introduced as frequently as every 6 months) the temptation not to comply with EU Regulations by some manufactures is increasing, since the risk of discovery is minimal [6].

- **Show cases in applications with a high replication potential** should be stimulated and promoted on a European scale;
- **Promote the use of appropriate intelligent lighting controls** (e.g. presence sensors and daylight dimming for indoor lighting and presence sensing with off-peak circulation dimming for outdoor lighting).
- **Public procurement** can be used to promote and to accelerate the penetration of advanced cost-effective solutions for applications with large potential;
- **Improve awareness through a variety of dissemination means for designers, specifiers and users in general**: LEDs can not only be used for retrofitting existing lighting, but also present new design and application opportunities in a variety of areas where conventional lighting has dominated;
- **Development of incentive programmes and other business oriented financing models (e.g. ESCOs)** based on European SSL quality/energy efficiency schemes with public and private sectors.

The combined implementation of the above-mentioned strategies in the LED lighting and display market at the European scale will offer the potential to not only significantly achieve energy savings and reduce CO_2 consumption in Europe, but also create jobs in this fast growing market.

3.3. Government policies around the world

Several countries around the world have recognized the potential contribution of SSL in achieving their overall objectives in the area of energy and environment, having large R&D programmes dedicated to this sector. At the same time they have identified the need for policies to address the barriers previously mentioned, as well as to accelerate the technology development through large R&D efforts.

This has been laid down in national policy documents and is accompanied by local supportive measures in both financing the

further development of SSL and achieving a quicker market penetration. Policies and programmes that address efficient lighting are generally targeted at the energy performance of specific lighting components, at the performance of entire lighting systems or at general transformation of the lighting market. In Europe so far only a few countries support SSL by a dedicated stimulation programme [5].

Table 4 summarizes the international experience to date on SSL policy.

Table 4
Examples of countries with policy statement on the contribution of SSL.
Source: CELMA & ELCFED [5].

Country	Korea	China	USA	Japan
Dedicated programme	√	√	√	√
Funds	√	√	√	√
CO_2 saving target			√	√
Social impact assessment	√	√	√	
Quality scheme			√	
Market surveillance			√	
Penetration target	√	√	√	√

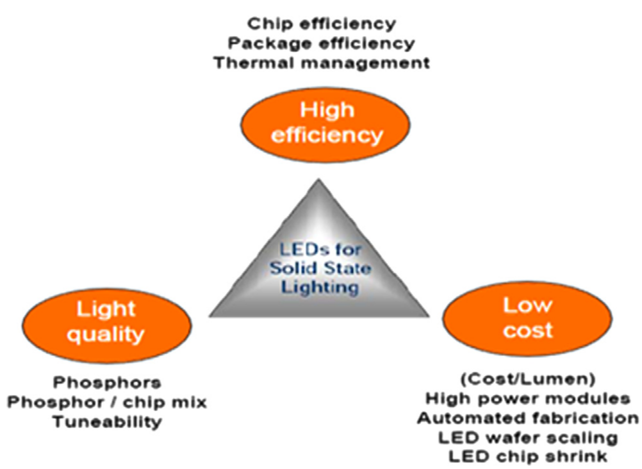

Fig. 18. Technical challenges for the large scale adoption of SSL.
Source: [25].

3.4. Supply-side challenges for the large scale adoption of SSL

A number of the challenges faced by the SSL industry have been investigated [5,51,52], and are summarized below, along with near-term opportunities and required strategies.

Despite outstanding efficiency increases in a short period, LEDs have only started to enter the lighting market in the last decade and there is still a large potential for improvement in order to become more competitive. The performance and efficiency of a LED as a light source is a function of the configuration of the LED package and also the configuration of the LED system as a whole, and there is a need for additional R&D work before LED lamps and systems can fully compete in the general lighting market. The initial cost for LED based systems also needs to come down, since it is often more than that of conventional systems.

Four key research and manufacturing themes were identified by the EU industry for its future development [5]:

- **The need for new materials achieving better performance at lower cost.** SSL will clearly be able to outperform existing lighting technologies in terms of efficacy, without sacrificing colour rendition;
- **Device integration and system architecture to serve the different applications targeted**. System architecture is the way to deal with the diversity of the different segments targeted, whilst creating volume leverage with standard processes and components;
- **The need for low-cost manufacturing. High speed assembly processes, larger area** deposition and patterning processes as well as a much higher degree of automation will be key in order to bring cost down from the present level;
- **Research on biological efficient lighting** is still very young and should be further strengthened and accelerated to take full advantage of potential benefits.

Figs. 18 and 19 show a summary of the challenges for the implementation of SSL described above.

4. SSL environmental impacts

LEDs are emerging not only as having high energy efficiency, but also as having some important environmental advantages

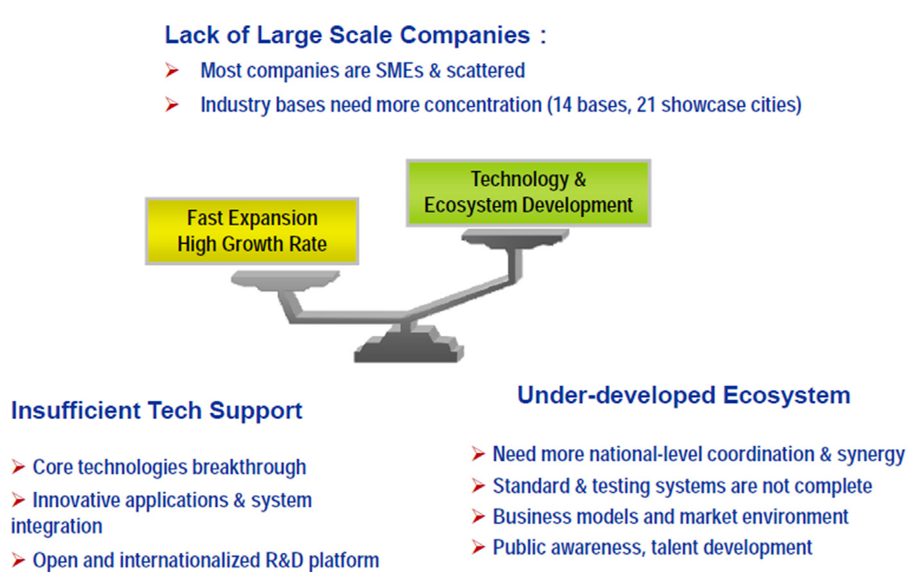

Fig. 19. Other challenges for the large scale adoption of SSL.
Source: [58].

compared to conventional light sources. Lower energy consumption leads to lower carbon emissions. Additionally, LEDs do not contain glass, filaments or mercury. This makes LEDs a much safer alternative to the current lighting technologies in retail, commercial and industrial applications [53,22,1]. Therefore LEDs have many economic and environmental advantages, being one of the most cost-effective technologies to reduce GHG. However, LEDs contain one or more chips (also called dies) that may contain very small amounts of mildly problematic materials such as arsenic, gallium, indium, and/or antimony (combined with nitrogen and phosphors) with potential environmental impacts, human health and ecological toxicity effects, especially when disposed of at the end of their lifecycle.

Furthermore, the LED chips are assembled into usable pin-type devices through the application of leads, wires, solders, glues, and adhesives, as well as heat sinks for thermal dissipation management. These ancillary technologies contain additional metals, such as copper, gold, nickel, and other metals, such as aluminium. It will be desirable to find proper ways to recycle these materials as well as gallium and indium as more LEDs enter the market.

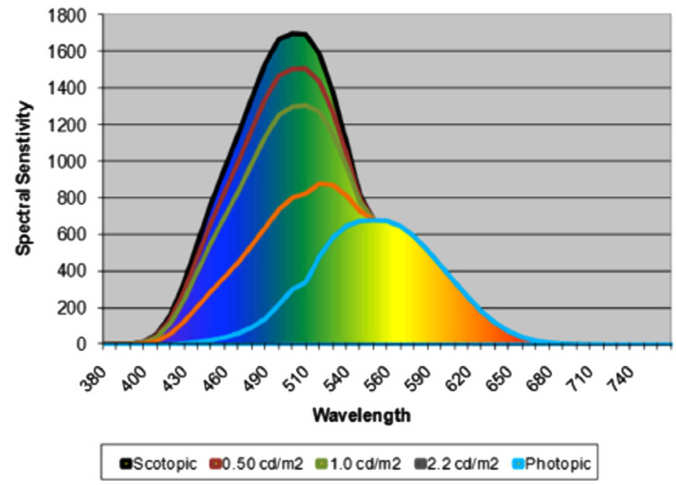

Fig. 20. Spectral sensitivity.
Source: [41].

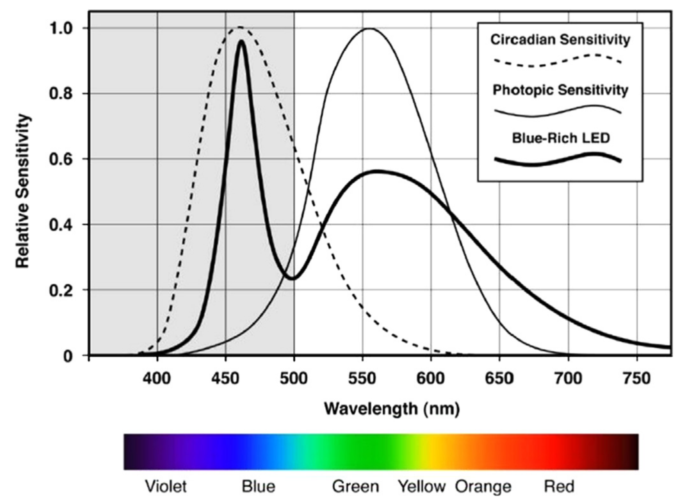

Fig. 21. Action spectrum for melatonin production.
Source: [41].

4.1. Potential health effects associated with LEDs

The potential health risks of these new light sources need to be explored. Due to the specific spectral and energetic characteristics of white LEDs, as compared to other domestic light sources, some concerns have been raised regarding their safety for human health, particularly potential harmful risks for the eye.

The evidence that artificial light may produce adverse consequences to human health and the environment remains incomplete. Photopic lumen is currently used in all lighting applications, be they interior or exterior, daytime or night-time. Investigations into the possible visual performance benefits of “spectrally enhanced” electric lighting for interior and exterior use are ongoing. Similarly, researchers are seeking to establish recommended requirements and restrictions for minimum daytime and maximum night-time exposures to light [41]. Due to the continuous growth of artificial lighting, namely in streets, roads, bridges, airports, commercial and industrial buildings, parking lots, sport centres and homes, this problem is increasingly debated and many countries have developed regulations to constrain the wasteful loss of light into the sky and environment.

SSL technology offers a number of potential advantages for outdoor lighting applications. LEDs can distribute light more directionally (minimizing spillage and light pollution), allowing for reduced average light levels in some applications, such as outdoor lighting, thereby further reducing power draw. The most efficient LEDs can already produce light using less wattage than would be required using a traditional light source. Reductions in connected load can be accomplished by a combination of improved luminaire efficacy and reduction or elimination of wasted light directed upward or outward beyond the target.

After moving outside from brighter lighting to indoor conditions, or during the transition from daylight to darkness, the human eye adapts to the low light levels. As part of this transition process, the eye gradually shifts from photopic (cone) vision toward scotopic (rod) vision, such that both rods and cones are contributing to vision. Therefore with low illumination levels the visual performance improves with lower wavelengths, as shown in Fig. 20. Lower wavelengths are derived from high colour temperature sources (e.g. 5.000 K and above).

With regard to human health impacts, to date it is clear that exposure to light at night decreases the melatonin production and secretion, and may interfere with circadian daily rhythms. Short wavelength light (light emitted below 500 nm, as indicated by the shaded section of the Fig. 21) has a greater tendency to affect living organisms through disruption of their biological processes that rely upon the natural cycles of daylight and darkness, such as the circadian rhythm as shown in Fig. 21. Human visual sensitivity is primarily in the green and yellow part of the spectrum and is depicted by the thin solid line. Circadian rhythms are controlled by light emitted within the dashed curve. The colour of light emitted by a typical bluish-white 5500 K LED is depicted by the bold line.

In general “cool” white LEDs are more efficient than those having a “warm” appearance, since short-wavelength spectral content plays a role in the photopic efficacy of LEDs.

Due to the fact that health may be impaired more by blue light, it is advisable to use warm white lamps (CCT to 3500 K) in residential areas, medium to cool white lamps (CCT from 4000 to 5000 K) in office areas, and cool white lamps (CCT equal or above 5400 K) on roads and in parking lots. High-efficacy (above 100 lm/W), low CCT warm-white LEDs are an environmental, ecological, and technological breakthrough that will help over time to minimize the impact of artificial lighting on the night environment. Their development is a significant technological achievement to encourage all LED manufacturers to strive for further reductions in short wavelength, blue light emission [41,18].

4.2. Life cycle analysis of SSL

Life cycle analysis (LCA) gives an overview of the energy and raw material use of a product from cradle to grave.

It considers also how much solid, liquid and gaseous waste and emissions are generated in each stage of the product's life (Fig. 22).

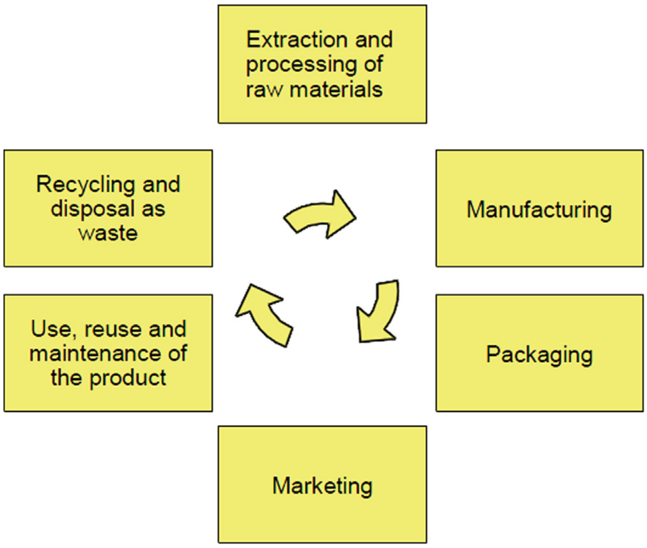

Fig. 22. Schematic of a life cycle analysis.
Source: [1].

The LCA is a useful tool in environmentally conscious product design. Environmental impact assessment of lamps over their life cycle is based on an inventory of environmental effects that result from all activities needed to generate a certain quantity of light. This indicates that resources (materials), lamp manufacturing and lamp disposal have a small impact on the environment compared to electricity consumption during lamp use. From an environmental point of view this means that energy efficient lamps are by far the best choice. During the life cycle of a lamp, 90% or more of the lamp's environmental impact is represented by the use phase, which is the energy consumption of a lamp. The environmental effect of electricity consumption originates mainly from the power generation, where fossil energy carriers like coal, natural gas or oil are converted into electricity, realizing GHG and other emissions (Fig. 23).

The results of the LCA can be used to compare products and technologies. The Ecodesign results indicate what paths should be adopted to minimize impacts in a cost-effective way. The results of an LCA are often given as environmental impact categories or as the so-called single scale indices. Environmental impact categories are for example primary energy, toxicological impacts, global warming potential and acidification potential. These values allow the comparison from the point of view of a single type of environmental impact. This makes the comparison of the total environmental impact of products easier.

The total cost of ownership with LED lighting systems (Fig. 24) is becoming increasingly more competitive, particularly for applications with a large number of operating hours.

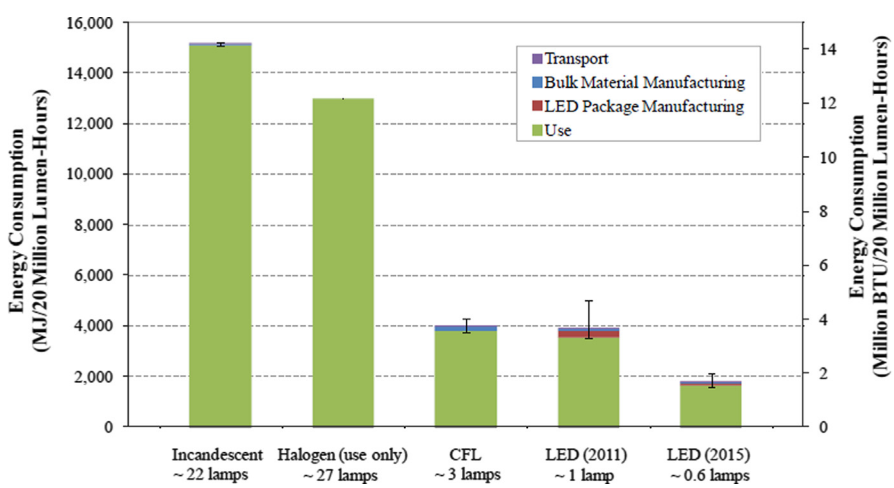

Fig. 23. Life-cycle energy of incandescent lamps, CFLs, and LED lamps.
Source: [28].

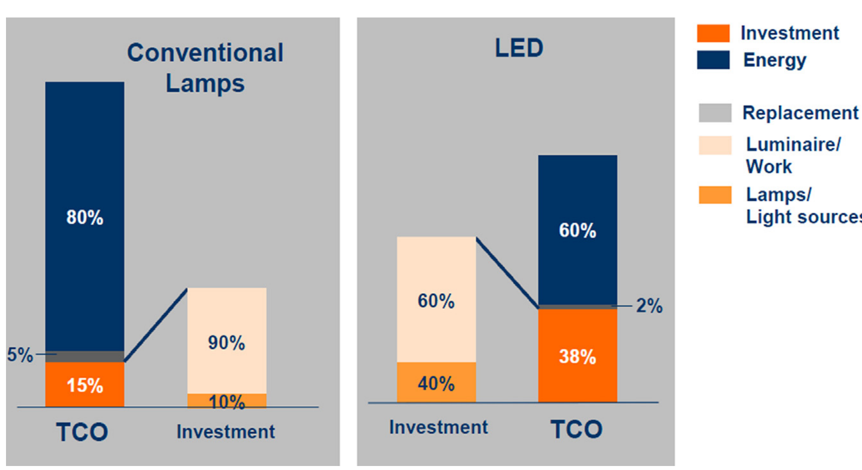

Fig. 24. Total cost of ownership (TCO) for different lighting systems.
Source: [36].

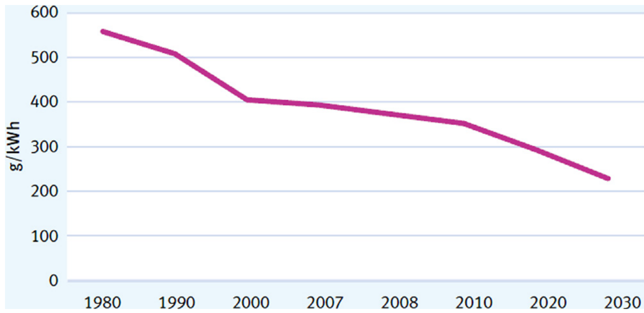

Fig. 25. CO_2 specific emissions.
Source: [17].

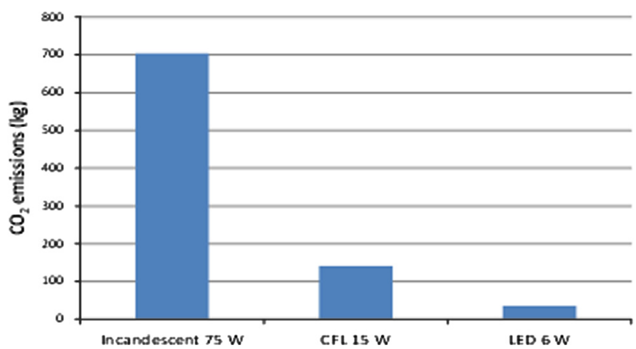

Fig. 26. Comparison of CO_2 emissions during life cycle (calculated for 25,000 h of time) of an incandescent lamp (12 lm/W), CFL (60 lm/W) and future LED light source (150 lm/W).
Source: Adapted [1].

Fig. 26 presents one LCA. It compares CO_2 emissions during the lifetime of an incandescent lamp, a CFL and a LED light source. A 75 W incandescent lamp with luminous efficacy of 12 lm/W, a 15 W CFL with luminous efficacy of 60 lm/W and a 6 W LED light source with luminous efficacy of 150 lm/W were compared to provide the same light output. The lifetime of the LED light source is assumed to be 25,000 h. The calculation was done for 25,000 lamp-burning hours. During this period, one LED, three CFLs and 21 incandescent lamps were needed. Most of the energy consumption and CO_2 emissions were caused in the operating phase of the lamps. CO_2 emissions of the electricity production were considered to be 370 g/KWh (typical emissions of a combined-cycle gas-turbine power plant and similar to average EU emissions). The CO_2 emissions during production of the lamps are also considered in the calculation [1] (Fig. 25).

The literature suggests that the ban of incandescent lamps and their replacement by equivalent compact fluorescent lamps (CFLs) will lead to important energy savings and associated reductions of greenhouse gas emissions (GHG). High-efficiency lighting systems using LEDs (over 120 lm/W overall plug efficacy) can cut the energy consumption by a factor of two compared to CFLs. LEDs with intelligent controls can further extend the energy savings overall, leading to GHG emission reductions of over 77 Mt of CO_2.

However, such LCAs should be analysed with caution. Indeed, there is no consensus on the scope of a light source LCA, that is, which environmental impacts to take into account. This is important in order to be able to compare the LCA with conventional light sources, so is the selection of testing conditions to use in the absence of testing standards. It is worth mentioning that manufacturing process data are difficult to obtain, as manufacturers are reluctant to divulge it. In addition, LED technology is evolving rapidly in terms of performance (luminous efficacy, lifetime, colour rendering and lumen maintenance) [52]. In view of the large product variety, it is difficult to choose the right luminaire or lamp. Finally, the impact of light itself, such as glare or light pollution, should be included. However, there is no method for quantifying the impacts of light on humans and flora and fauna.

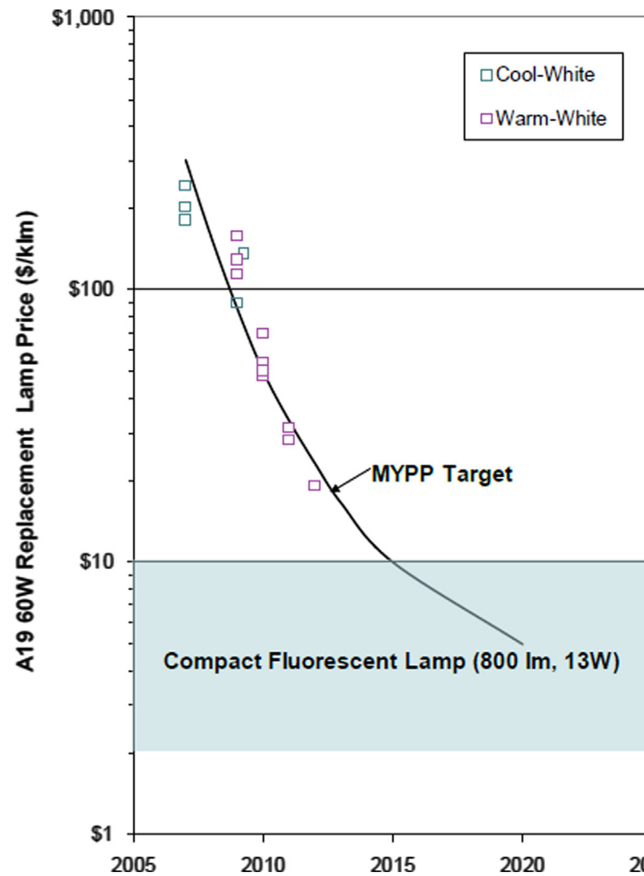

Fig. 27. White light integrated LED lamp price projection (logarithmic scale).
Source: [46].

Despite the above-mentioned caveats and the uncertainties in the assessment of the end-of life, LCAs indicate that the energy consumption in use is the major environmental aspect. For LED lights, the situation is more favourable than for traditional light sources.

In conclusion, there is a need for conducting a full LCA of LED light sources. Further research into LED lighting LCA would be necessary to come up with a definite outcome.

5. Future lighting energy consumption in Europe

5.1. Future trends

Due to a variety of energy efficiency improvements, as the demand for artificial lighting services grows, the energy consumption required to supply is increasing but at a slower rate due to the use of more energy-efficient technologies.

In the previous chapters it was shown that LED lighting can basically cover all applications to replace existing technologies leading to large energy and maintenance cost savings. It is expected that applications in street lighting, in the tertiary/commercial sector and in industry will experience a faster transition due to the large number of operating hours leading to shorter payback times.

In the residential sector a lower number of operating hours and the relatively large cost of LED bulbs may slow down the consumer adoption rate. Recent news on the market points to the availability

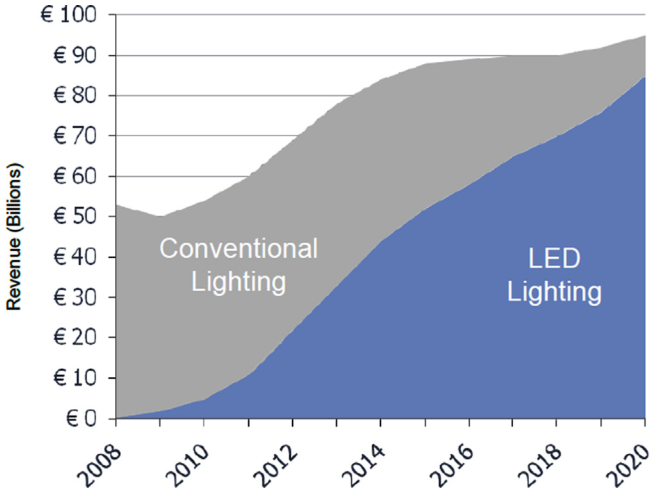

Fig. 28. Lighting market transformation.
Source: [56].

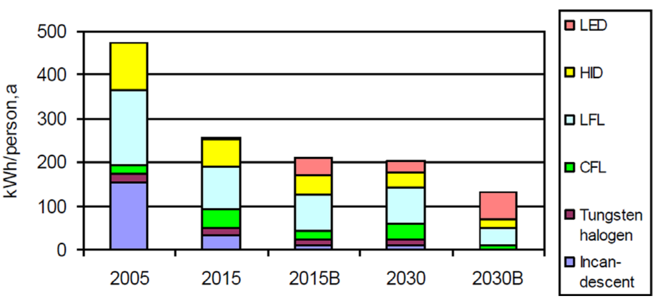

Fig. 29. Scenarios of electric energy consumption for lighting in IEA countries.
Source: [21].

in the near future (well before 2015) of competitive LED bulbs to replace both conventional incandescent and CFL lamps (Fig. 27).

The rate of transition of conventional lighting to LED based lighting will depend upon many factors mentioned in the section on barriers to SSL development, but the outlook is for a massive market transition as shown in Fig. 28, particularly as prices drop and performance increases.

Fig. 29 shows the scenarios of electric energy consumption for lighting in IEA Countries, in which the scenarios 2015B and 2030B are based on increased use of LEDs, with the corresponding impressive reduction in the electricity consumption. There is still considerable uncertainty in the evolution of SSL penetration rate, but there are strong reasons to accelerate the market transformation.

5.1.1. *Residential buildings*

Lighting consumption in Residential Buildings in Europe is characterized in Fig. 30 based on the IEE REMODECE monitoring project [11]. About 3/4 of the residential lamps in EU homes are either plain incandescent or halogen incandescent. Table 5 shows the average lamp efficacy in the residential sector in several EU countries in 2005. Since 2000 incandescent lamps have increasingly been replaced by CFLs, and by 2010 the average lamp efficacy in the EU residential sector should be around 35 lm/W and moving upwards. If full replacement by CFL was achieved that value would be around 60 lm/W. LED lamps are able to provide much better performance and by 2020, lamps with an efficacy well over 120 lm/W should be available. The progressive replacement of residential lamps can lead therefore to savings over 50% compared with a scenario with no LEDs.

5.1.2. *Tertiary sector (commercial buildings)*

Lighting consumption in tertiary buildings in Europe is characterized in Table 6, and there is an ongoing replacement of T8

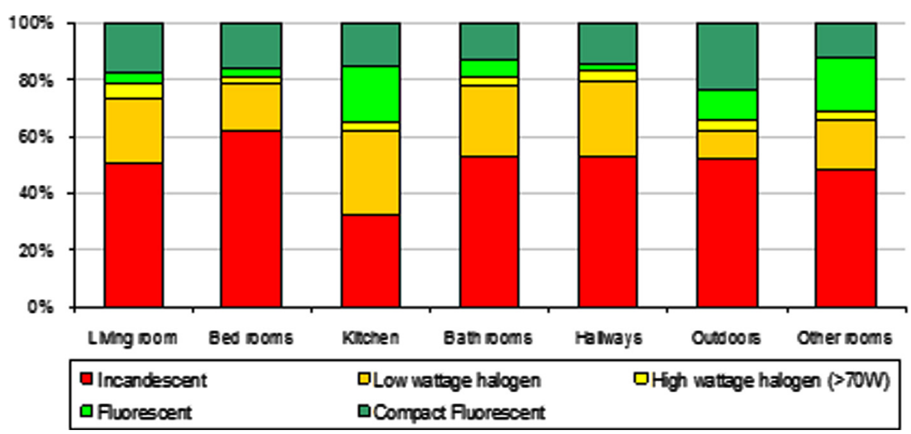

Fig. 30. Lighting consumption in residential buildings in Europe, based on the REMODECE project.
Source: [11].

Table 5
Estimated national average residential lighting characteristics for some IEA member countries.
Source: [22].

Countries	Lighting electricity (kWh/household, a)	No. of lamps per household	Average lamp luminous efficacy (lm/W)	Light consumption on (Mlmh/m^2, a)	Lighting electricity consumption (kWh/m^2,a)	Lamp operating hours per day
UK	720	20.1	25	0.21	8.6	1.60
Sweden	760	40.4	24	0.16	6.9	1.35
Germany	775	30.3	27	0.22	9.3	1.48
Denmark	426	23.7	32	0.10	3.3	1.59
Greece	381	10.4	26	0.09	3.7	1.30
Italy	375	14.0	27	0.09	4.0	1.03
France	465	18.5	18	0.22	5.7	0.97
USA	1946	43.0	18	0.27	15.1	1.92
Japan	939	17.0	49	0.49	10.0	3.38

Table 6
Estimated average lighting characteristics of commercial/tertiary buildings.
Source: [22].

Region	Average lighting power density (W/m^2)	Annual lighting energy consumption per unit area (kWh/m^2)	Average operating period (h/a)	Lighting system efficacy (lm/W)	Commercial building floor area (billion m^2)	Total electricity consumption (TWh/a)
Japan/Korea	12.6	33.0	2583	62.7	1.7	54.6
Australia/NZ	16.5	31.7	1924	43.5	0.4	12.7
North America	17.4	59.4	3928	50.1	7.3	435.1
OECD Europe	15.5	27.7	1781	46.1	6.7	185.8
OECD	15.6	43.1	2867	49.6	16.1	688.2

Table 7
LED luminaire development.
Source: [46].

Metric	2013	2015	2020	Goal
Package efficacy (lm/W)	129	162	224	266
Thermal efficiency	85%	88%	90%	93%
Efficiency of driver	85%	87%	90%	92%
Efficiency of fixture	85%	89%	92%	92%
Resultant luminaire efficiency	62%	68%	74%	79%
Luminaire efficacy (lm/W)	80	110	166	210

Table 8
SSL savings potential in 2030.
Source: [59]

	Consumption 2007 (TWh)	Consumption 2030 high LED scenario (TWh)
Residential*	84	42
Tertiary/commercial**	164	74
Industry *	100	50
Street/outdoor ***	60	33
Total	408	199

* Assumes a 50% savings potential.
** CELMA-ELCFED – estimated a 55% savings potential.
*** IEE-Project E-Street – identified a 64% savings potential.

lamps by T5 lamps with electronic ballast (efficacy up to 100 lm/W). The average lamp efficacy should now be around 60 lm/W and moving upwards. LED luminaires will be able to provide much better performance and by 2020, luminaires with efficacy over 200 lm/W should be available (Table 7), as projected by the US DoE. The progressive replacement of fluorescent lamps can lead therefore to savings over 50% compared with a scenario with no LEDs.

5.1.3. *Industrial buildings*

Most of the electricity in industrial buildings is used for industrial processes. Although the share of lighting electricity of the total electricity consumption in industrial buildings is only 9%, it accounted for about 18% of the total global lighting electricity consumption in 2005 [22]. Compared to the residential and commercial sectors, there have been very few surveys and studies about the industrial building lighting energy consumption. The IEA estimation of European OECD countries' industrial lighting consumption in 2005 was 100.3 TWh per annum.

Amongst the three sectors (residential, commercial and industrial), the industrial sector has the highest average efficacy. This is due to the fact that most of the light in industrial buildings comes from efficient fluorescent lamps and HID lamps. According to the IEA estimation for OECD Europe, the average lamp luminous efficacy in the industrial sector is 82 lm/W. Fluorescent lamps contribute to about 62% of OECD industrial illumination, 37% of HIDs and 1% of others.

LED luminaires will be able to provide much better performance and by 2020, luminaires with efficacy of over 200 lm/W should be available (Table 7). The progressive replacement of fluorescent lamps and HID lamps can lead therefore to savings over 50% compared with a scenario with no LEDs.

5.2. *Energy savings potential in Europe*

The consumption in the 2030 BAU Scenario assumes net zero growth, as new technologies other than LEDs would compensate for the growth in the consumption of lighting services (Table 8).

The estimated savings potential through the application of LED lighting systems in the EU is around 209 TWh, which translates into 77 Mt of CO_2. The economic benefits translate into the equivalent annual electrical output of about 26 large power plants (1000 MW electric), with the value of 30 billion Euros of saved electricity costs assuming an average price of 0.15 €/kWh.

Based on the above-mentioned savings projections, it can be said that LED Lighting systems present one of the largest cost-effective opportunities for massive electricity savings with the associated economic and environmental benefits.

5.3. *SSL potential in other parts of the world*

In developing countries, particularly in rural areas, having basic lighting for the daily activities is a privileged status. Used as a development tool LEDs can significantly improve the living conditions of the poor, enhancing their safety and health, improving literacy, protecting the environment and creating opportunities for income generation [33]. There are approximately 2 billion people without access to electricity. These people use traditional fuels (e.g. kerosene or bio-mass) that degrade their environment and cost over 1500 times more per lumen-hour than conventional lighting using electricity in developed countries.

Solid-state lighting can be highly beneficial to developing countries by providing efficient lighting technology that can be implemented in small increments and that works well with small, micro-power systems (e.g. solar photovoltaic, small hydroelectric generators) enabling them to overcome more costly and less efficient types of energy distribution [54]. There is a need for a massive rural electrification effort and LEDs can play a key role to provide low cost lighting services.

Due to a number of geographical, political, and cultural factors, LEDs are likely to make even more remarkable progress in Asia. The value-based LED share in the Asian lighting market was over 10 percent in 2011 thanks to the fast penetration of LEDs in Japan and China, as shown in Fig. 31. Due to the severe energy shortage and greatly increasing awareness of the need to save energy after the Fukushima disaster in 2011 and the resulting seven-percent reduction of Japan's energy supply, the LED penetration has accelerated, such that LED lamps are forecasted to account for 30 percent of non-HID lamps sold in Japan in 2020. Lighting accounts for 16% of Japan's

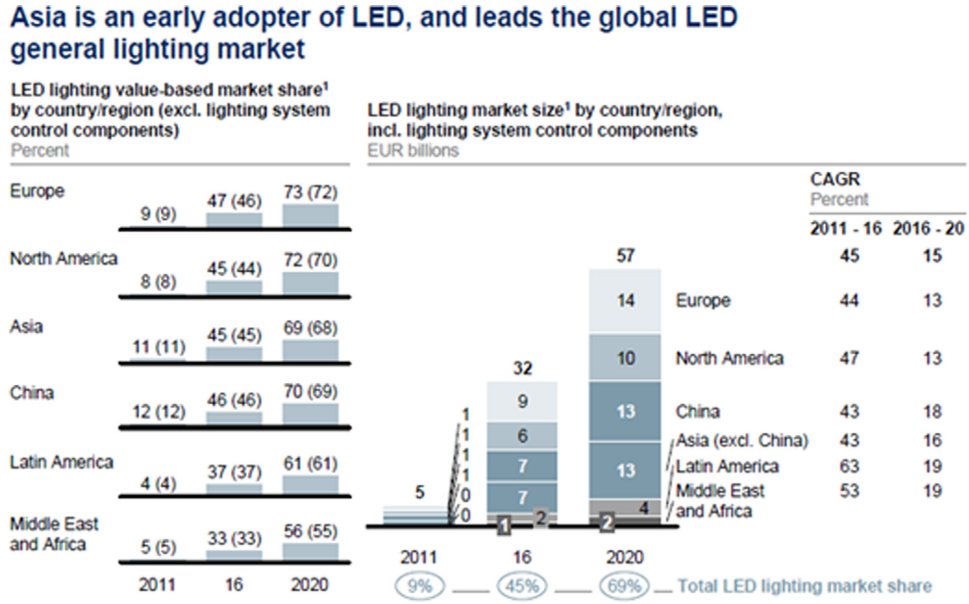

Fig. 31. LED lighting market share by country/region.
Source: McKinsey & Company, Inc [26].

electricity consumption. If all lighting in Japan were switched to LEDs, Japan's electricity consumption could be reduced by 9% [23].

Likewise, China is making a push for LED light sources to supplant other lighting technologies in an effort to mitigate the rising demand for power generation. China also has a relatively high LED penetration, at around 12 percent in 2011. The Chinese government has set a target for LEDs to constitute 30 percent of domestic lighting market sales in 2020. In 2012, China experienced the fastest growth of any country regarding LED replacement lamps. The China Solid State Lighting Alliance estimates that domestic shipments of LED lights in 2012 amounted to 130 million units, or 3.3 percent of all lighting products [46].

In the USA under a LED intensive scenario, the DoE projects in 2030 an annual energy savings from solid state lighting of approximately 297 TWh [46]. The value-based LED lighting market share for 2011 is estimated at around 8 percent in North America, climbing to around 45 percent in 2016 .

The rest of the world (Latin America, the Middle East, and Africa) makes up a much smaller share than the other regions in terms of the overall general lighting and LED markets. The value-based LED lighting market share in 2011 is estimated at 4 percent for Latin America and 5 percent for the Middle East and Africa combined. Those regions are also seeing fast LED lighting growth, with a penetration of over 30 percent forecast for 2016. Government industry policy may have a significant impact on LED penetration in Latin America. Import duties on lighting fixtures are high in Latin American countries. Unless production facilities are locally available, LED fixtures could become even more expensive [26].

6. Conclusions and recommendations

Solid-state lighting is a high energy efficiency technology in a fast technological improvement phase, with multiple advantages, presenting at the same time decreasing costs with the following key attributes:

- Potentially more energy-efficient than other light sources;
- Very long lifetime, leading to lower maintenance costs;
- Good physical robustness and compactness;
- Lowest environmental impacts over the lifecycle of the product;
- Lowest life-cycle cost for an increasing number of applications, due to the decreasing cost trend;
- Largest choice of options in terms of light characteristics. There is a diversity of lamps, fixtures and applications which can be addressed with SSL different solutions.

Therefore SSL is well positioned to become the dominant efficient light source by 2020. Progressively the market will adopt SSL solutions to replace conventional technologies.

The estimated savings potential through the application of LED lighting systems in the EU is around 209 TWh, which translates into 77 Mt of CO_2. In the USA the projected electricity savings are also very large, reaching almost 300 TWh. The economic benefits translate into the equivalent annual electrical output of about 26 large power plants (1000 MW electric), with the value of 30 billion Euros of saved electricity costs assuming an average price of 0.15 €/kWh. Energy savings can be further increased with intelligent light control to minimize waste, increase convenience and safety.

The main technical, economical, and market barriers to the LEDs' large scale market adoption are the following:

- Cost: LED-based general illumination sources face a higher initial cost in comparison with conventional lighting technologies;
- Luminous efficacy: The luminous efficacy (lm/W) of LEDs is already above 100 lm/W, but it can still improve to compete with other conventional HID lighting solutions;
- Testing uncertainty: The reported lumen output, efficacies and lifetimes of LED products in the market do not always match laboratory tests of performance;
- The market lacks suitable uniform testing standards that measure efficacy, lifetime and other critical performance attributes such as reliability and compatibility in a consistent manner. However, the available LED standards have limited coverage of LED products, and significant variations exist between the product scope and test methods of different standards;
- Manufacturing process uniformity: Lack of process and component uniformity will be an important issue for LEDs and is a barrier to reduced costs as well as a problem for uniform quality of light;

- Poor quality products in the market: The EU market is being invaded by relatively low-cost poor quality (low efficacy, poor colour rendition, and short lifetime) products coming from Asia;
- Lack/high cost of capital: This traditional market barrier is associated with the lack and/or high cost of capital required to make larger investments in the implementation LED lighting systems;
- Aversion to risk: The uncertainty of product performance, particularly the required lifetime to justify the investment, can negatively influence decision makers;
- Lack of information: LED-based lighting remains a new technology that is not well known in the marketplace;
- Inadequate/split incentives: Many decisions about lighting technologies are taken by designers and stakeholders who are not the final users of the technologies.

Although a number of EU Member States have taken measures, especially in the field of funded scientific research, the future challenges related to market penetration, international benchmarking, as well as definition and implementation of technological leadership have to be addressed on a European level. The need for concerted and integrated European policies is obvious when looking at the supply and demand side of the industry. The strategies described below, structured in three groups, can be used to overcome existing barriers and promote a faster penetration of SSL products.

The following actions should be directed at the supply side to support performance, quality and price improvement:

- Collaborative effort needs to be promoted to increase the performance of SSL solutions: from LED chip, lamp to luminaire and lighting solutions – cost and quality are in focus. The lighting and small and medium enterprises based luminaire industry needs to act at the European scale to overcome fragmentation and to gain critical mass in the latest SSL development and broad deployment;
- Continue to support LED R&D activities: both pre-competitive and competitive research that will improve efficacy and reduce cost such as efficiency drop, thermal performance, phosphors, light extraction and driver performance;
- Support of a value chain approach: A lot emphasis has been placed on breakthrough research (e.g. FP6 and FP7 Programmes) and less attention on the cost intensive downstream activities of industrialization and commercialization, i.e., applied research, system integration and market validation;
- Support device integration and system architecture to serve the different applications targeted;
- Support development of low-cost manufacturing. High-speed assembly processes, larger area deposition and patterning processes as well as a much higher degree of automation will be key in order to bring cost down from the present level;
- Support research on biological efficient lighting.

To assure a broader acceptance and credibility of SSL products, there is a need to establish international standards, labels and quality schemes jointly with industry, including the following:

- Improved international harmonized test standards addressing all key aspects of SSL lighting performance (namely efficacy, lumens, watts, correlated colour temperature (CCT), colour rendering index (CRI) and lifetime) are required to ensure a level playing field for a competitive market;
- Minimum efficiency performance standards to remove from the market products; existing lighting standards should be expanded at the EU level (harmonized if possible through international cooperation) to cover other products and sectors with progressive stringency levels, as SSL technology develops;
- Energy labels, such as those of the European Union LED Quality Charter or ENERGY STAR, are very important in establishing minimum performance levels, ensuring the credibility of SSL products;
- Market surveillance: As compliance with European requirements is based on self-certification by the manufacturer or distributors, market surveillance by the EU Member States seems crucial to avoid unfair competition and customer dissatisfaction.

In addition to the above-mentioned strategies the following market transformation actions can be applied:

- Show cases in applications with a high replication potential should be stimulated and promoted on a European scale;
- Public procurement can be used to promote and to accelerate the penetration of advanced cost-effective solutions for applications with large potential;
- Promote the use of appropriate intelligent lighting controls (e.g. presence sensors and daylight dimming for indoor lighting and presence sensing with off-peak circulation dimming for outdoor lighting);
- Improve awareness through a variety of dissemination means for designers, specifiers and users in general: LEDs can not only be used for retrofitting existing lighting, but also present new design and application opportunities in a variety of areas where conventional lighting has dominated;
- Development of incentive programmes and other business oriented financing models (e.g. ESCOs) based on European SSL quality/energy efficiency schemes with public and private sectors.

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